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A REVISED FORMULA FOR THE CALCULATION OF GAMMA-RAY SHIELDING PROPERTIES OF SHELTER ENTRANCEWAYS

Technical Note N-843

Y-F008-08-05-201, DASA 11.058

by

C. M. Huddleston and W. C. Ingold

ABSTRACT

An improved formula has been devised for the calculation of gamma-ray dose attenuation in two-legged air ducts through concrete. Comparisons are given between the predictions of the simple empirical formula and the results of measurements as well as predictions obtained by a more complicated computational technique. The accuracy of the empirical formula is discussed. It is shown that the formula is highly accurate, having essentially zero bias and a standard deviation of less than 14 percent of the correct value.

INTRODUCTION

In earlier publications an empirical formula was developed for predicting the effectiveness of two-legged air ducts through concrete for the attenuation of gamma radiation.[1,2] Results were directly applicable to the case of radiation streaming through entranceways and air ducts leading into protective structures.

During the past two years, however, certain events have taken place which make it desirable to revise the earlier formula. Chapman has modified and improved his computer technique for calculating the streaming of gamma radiation through ducts.[3] Also, Chapman has made additional measurements on the streaming of gamma rays from Au^{198}, Cs^{137}, and Co^{60}.[4]

In view of the above developments, a reappraisal was made of the earlier empirical formula in the light of information presently available. This note is concerned with the development of a new empirical formula. Some sample problems are worked to demonstrate its usefulness. The accuracy and limitations of the formula are discussed. A statistical analysis is used to show that the formula has essentially no bias and a quite small random error.

DEVELOPMENT OF THE FORMULA

The formula as originally developed to approximate attenuation factors in two-legged concrete ducts was[1,2]

$$\frac{D}{D_o} = 0.25 \frac{\left(\frac{H}{W}\right)^{0.907} W^{2.864}}{L_1^{2.534} L_2^{2.667} E_o^{0.710}} \qquad (1)$$

where

D_o = dose rate in mr/hr at a distance from the source of one foot in air

D = dose rate in mr/hr inside the shelter

H = height of entranceway in feet

W = width of entranceway in feet

L_1 = length in feet of first leg of duct

L_2 = length in feet of second leg of duct

E_o = average energy of source gamma radiation in Mev

The formula was considered to be valid when the following inequalities are true

$0.662 \leq E_o \leq 3.000$ Mev

$1.0 \leq H \leq 6.0$ feet

$1.0 \leq W \leq 6.0$ feet

$2 \leq L_1 \leq 36$ feet

$1 \leq H/W \leq 2$

$L_1/H \geq 6$

$L_2/H \geq 6$

$L_1/W \geq 2$

$L_2/W \geq 2$

The formula had a safety factor already incorporated into it, so that one could be 95-percent certain that the actual attenuation factor, D/D_o, is at least as small as the attenuation factor calculated by the formula.

Because of the availability of both new experimental data and an improved computerized calculational technique, it was decided to seek an improved empirical formula. The first attempt was to fit data to a formula of the type

$$\frac{D}{D_o} = \frac{K\,(H + \Delta H)^{\alpha_1} (W + \Delta W)^{\alpha_2}}{L_1^{\alpha_3} L_2^{\alpha_4} E_o^{\alpha_5}} \qquad (2)$$

where K and the α's are adjustable parameters. The width and height were incremented by an amount depending on E_o, to account for the fact that scattering of gamma rays does not occur at the surface but at some depth below the surface of the scatterer. This technique of mathematically incrementing the physical dimensions of the duct was successfully used by Chapman in his computer calculations.[3]

It was soon found, however, that Equation 2 did not give an appreciably better fit than

$$\frac{D}{D_o} = K \frac{(H/W)^{\alpha_1} W^{\alpha_2}}{L_1^{\alpha_3} L_2^{\alpha_4} E_o^{\alpha_5}} \tag{3}$$

Since Equation 3 is simpler than Equation 2, it was decided to forego the refinement of incremented cross sectional dimensions. Curve fitting yielded the following formula

$$\frac{D}{D_o} = 0.244 \frac{\left(\frac{H}{W}\right)^{.9758} W^{3.048}}{L_1^{2.701} L_2^{2.705} E_o^{0.581}} \tag{4}$$

Comparison of the above with Equation 1 shows minor changes in the adjustable parameters. These changes result from additional information which has become available since Equation 1 was postulated.

Study of Equation 4 indicated further simplification might be in order. The W in H/W was multiplied out and other rounding off of exponents was performed, producing

$$\frac{D}{D_o} = \frac{HW^2}{4(L_1L_2)^{2.7} E_o^{0.6}} \tag{5}$$

It is noted that Equation 5 is not dimensionally correct, since the left hand side is dimensionless while the right hand side has units feet$^{-2.4}$ Mev$^{-0.6}$. This failing is a common fault of empirical equations. Although numerically correct results are obtained, there remains the conceptual difficulty of unequal units. One should, then, imagine that the right hand side of Equation 5 is multiplied by a constant K which has magnitude unity and dimensions of feet$^{2.4}$ Mev$^{0.6}$. The fact that such units are not physically meaningful is a consequence of the fact that the equation is an empirical one which has not been derived from purely physical considerations.

Since a statistical analysis indicated that Equation 5 fit the available data almost as well as Equation 4 fit the data, Equation 5 is adopted, and it is recommended for calculations of attenuation of gamma-ray dose in two-legged air ducts through concrete whenever the following inequalities hold:

$0.3 \le E_0 \le 3.7$ Mev

$1.0 \le W \le H \le 6.0$ feet

$2.0 \le L_i \le 24.0$ feet, $i = 1, 2$

$L_i/H \le 6.$, $i = 1, 2$

$1.0 \le H/W \le 2.0$

It will be noted that the inequalities listed above are somewhat different from the conditions listed earlier for the validity of Equation 1. It is believed that the set of inequalities specified for Equation 5 are more reasonable for the case of protection from fallout radiation.

In later sections, the curve-fitting procedure will be described and the accuracy of Equation 5 will be discussed.

CURVE FITTING

Having decided to fit an equation of the form of Equation 3, the next step was to select the data to be fit and to perform the curve-fitting analysis.

Fifty experimental measurements, corresponding approximately to those reported by Chapman,[3] were chosen. Also, Chapman's computer code was used to calculate the same cases. This gave an additional 56 datum points, because two computer calculations were performed for each of the six cases involving the gamma rays of Na^{24}, since Na^{24} has two well separated gamma-ray energies. In addition, 117 fictitious cases were selected at random from the domain of interest. Those cases were calculated using Chapman's code to provide another 117 datum points. Since agreement between Chapman's calculations and experiment is excellent in most cases, it seemed reasonable to believe that his calculations could be trusted to be accurate anywhere within the domain of energy and duct geometry where it has been tested.

The method for selection of the 117 fictitious cases consisted of choosing lengths, widths, and heights at random from the domain of interest; i.e., subject to the stipulated inequalities. Thus all allowable dimensions were equally likely to be chosen.

Since there is little or no experimental data for energies above 3.0 Mev, and since energies resulting from fallout are in the neighborhood of 1 to 2 Mev, it was decided to limit the energy range to from 0.3 Mev to 3.7 Mev, with concentration around 2.0 Mev. This was accomplished by choosing energies at random from a population of energies with a maximum density at 2.0 Mev and with a density falling off linearly from the maximum to zero at 0.3 Mev and 3.7 Mev. A histogram of the energies actually selected is shown in Figure 1.

Using the 223 cases described as data, the IBM-1620 computer program, "Stepwise Regression Analysis Program" (STRAP) Revised[5] was used to perform the analysis. The parameters were found to be

$$K = 0.244 \qquad \alpha_3 = 2.701$$
$$\alpha_1 = 0.9758 \qquad \alpha_4 = 2.705$$
$$\alpha_2 = 3.048 \qquad \alpha_5 = 0.581$$

The formula then became

$$\frac{D}{D_o} = .244 \frac{\left(\frac{H}{W}\right)^{.9758} W^{3.048}}{L_1^{2.701} L_2^{2.705} E_o^{.581}} \tag{4}$$

The 223 cases were then recalculated using Equation 4 and the results compared with the measured results and those calculated with Chapman's code.

Figure 2 shows a histogram of the ratios obtained when the 223 results of Equation 4 were divided by the 223 datum points. The mean was found to be 1.011, and the standard deviation was found to be 0.128. Also on Figure 2 is a theoretical Normal density function having those values for mean and standard deviation.

A χ^2 goodness-of-fit test was performed. The value of χ^2 obtained was 6.91. A χ^2 of 6.4 would disprove the assumption of normality at the 50-percent confidence level, while a χ^2 of 9.0 would disprove normality at the 75-percent confidence level. Thus, the χ^2 analysis provided no reason to disbelieve the assumption of normality. Therefore, normal theory was used to make predictions regarding the population of all possible ducts within the domain of interest.

Next, the ratios between datum points and formula results were obtained for the simpler formula

$$\frac{D}{D_o} = \frac{HW^2}{4(L_1 L_2)^{2.7} E_o^{0.6}} \tag{5}$$

Figure 3 shows the histogram of the ratios obtained. While the mean, 1.007, more closely approximated the assumed mean of 1.000, the standard deviation was somewhat larger, 0.135. Thus, approximately 95 percent of the cases lie within ±27 percent of the Chapman solution and/or the measured results, and approximately two-thirds are within ±13.5%.

Since Equation 5 is simple and gives satisfactory agreement with the data, Equation 5 is recommended for calculations of gamma-ray streaming through concrete ducts.

USING THE FORMULA

In order to obtain conservative (safe) estimates of the dose rate inside a shelter, use is made of the formula

$$\frac{D}{D_o} = \frac{HW^2}{3(L_1L_2)^{2.7}\ E_o^{0.6}} \tag{6}$$

A simple way is now described for using the formula.

Enter Figure 4 with the value of L_1 for the duct of interest, and find the corresponding value for $L_1^{2.7}$. Similarly, find $L_2^{2.7}$, also from Figure 4.

Find $E_o^{0.6}$ from Figure 5. If the energy, E_o, is unknown, assume $E_o = 2$ Mev.

Now substitute into Equation 6 to find a conservative estimate of the attenuation factor of the entranceway.

It should be noted that all the discussion up to this point has been concerned with a point isotropic gamma-ray source located on the centerline axis just at the outside opening of the entranceway. In a radiation shelter, however, what is really of interest is the protection factor; i.e., the ratio of the dose rate at 3 feet above the ground in an unprotected place to the dose rate in the shelter. It is, therefore, necessary to modify Equation 6, in order to obtain a conservative estimate of the desired quantity, PF, protection factor. Define

$$Fg = \frac{D}{D_o} \tag{7}$$

where D/D_o is given by Equation (6).

The protection factor is then defined as

$$PF = \frac{1}{FgFs} \tag{8}$$

where Fs is a source factor. For fallout radiation, reference is made to Figure 6 (due to J. C. LeDoux). When the first leg is horizontal

$$Fs \approx L_1^2\ A_v$$

For a vertical first leg, where the aperture covering is contaminated,

$$Fs \approx L_1^2\ A_h$$

For a vertical first leg, where the aperture covering is not contaminated,

$$Fs \approx L_1^{\ 2} A_a$$

The three different cases are shown in Figure 6, which also gives values for the factors A_v, A_h, and A_a.

SAMPLE PROBLEMS

The simplified empirical formula will now be used to calculate dose rates within three sample ducts.

Case 1

Consider a 1-foot square duct with L_1 = 3.5 feet and L_2 = 2.0. The source energy is 1.25 Mev, corresponding to Co^{60}.
Equation 5 is now used:

$$\frac{D}{D_o} = \frac{(1)\ (1)^2}{4(3.5 \cdot 2.0)^{2.7}(1.25)^{0.6}} = 0.114 \times 10^{-2}$$

The above can be obtained by computer calculation, by slide rule, or by logarithms.
For the same case, Chapman's computer code gives the answer:

$$\frac{D}{D_o} = 0.1223 \times 10^{-2}$$

Terrell[6] measured this duct situation as:

$$\frac{D}{D_o} = 0.108 \times 10^{-2}$$

Case 2

Consider a 6-foot-square duct with L_1 = 12 feet and L_2 = 15 feet. The source energy is again 1.25 Mev.
Equation 5 gives

$$\frac{D}{D_o} = \frac{6 \cdot 6^2}{4(12 \cdot 15)^{2.7}\ (1.25)^{0.6}} = 0.385 \times 10^{-4}$$

Chapman's code gives

$$\frac{D}{D_o} = 0.4068 \times 10^{-4}$$

The measured value was[7]

$$\frac{D}{D_o} = 0.354 \times 10^{-4}$$

Case 3

As a final case, consider a 3-foot square duct with $L_1 = L_2 = 7.5$ feet. The source energy is 0.662 Mev, corresponding to Cs^{137}.

Equation 5 gives

$$\frac{D}{D_o} = 0.163 \times 10^{-3}$$

Chapman's code gives

$$\frac{D}{D_o} = 0.1662 \times 10^{-3}$$

The measured value was[4]

$$\frac{D}{D_o} = 0.156 \times 10^{-3}$$

Thus it is seen that in all three cases there is good agreement between the simple formula and both Chapman's computer calculations and experimental values.

CONCLUSIONS

It has been shown that the attenuation factor of a two-legged air duct through concrete can be satisfactorily fit by the empirical equation

$$\frac{D}{D_o} = \frac{HW^2}{4(L_1L_2)^{2.7}\ E_o^{0.6}} \tag{5}$$

for fallout gamma radiation over the domain of duct dimensions of interest.

The formula is a good one in the sense that there is no apparent bias in its predictions. It does, however, have a standard deviation of 13.5 percent. Therefore, a safety factor should be incorporated to assume that predictions of dose rates inside shelters will be unlikely to be low. A recommended conservative formula is

$$\frac{D}{D_o} = \frac{HW^2}{3(L_1L_2)^{2.7}\ E_o^{0.6}} \tag{6}$$

Using the above formula, one can be 95-percent certain that the actual dose rate will not be greater than the formula predicts.

In order to obtain the protection factor in a fallout field use is made of the equation

$$PF = \frac{1}{FgFs} \tag{8}$$

The above equation will give a conservative estimate of the protection factor of a fallout shelter, assuming radiation can enter only through the entranceway.

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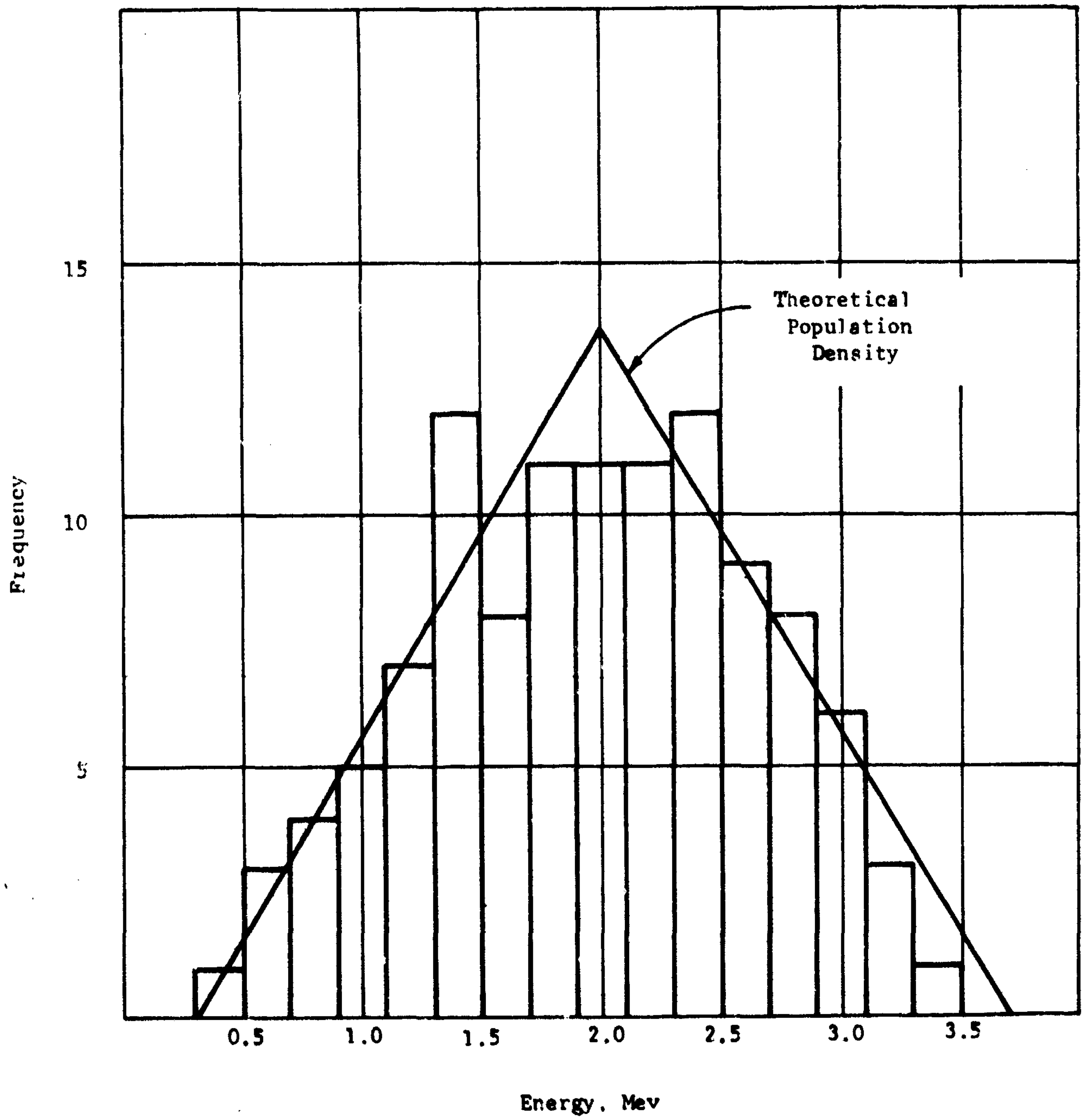

Figure 1. Histogram of 117 randomly selected energies.

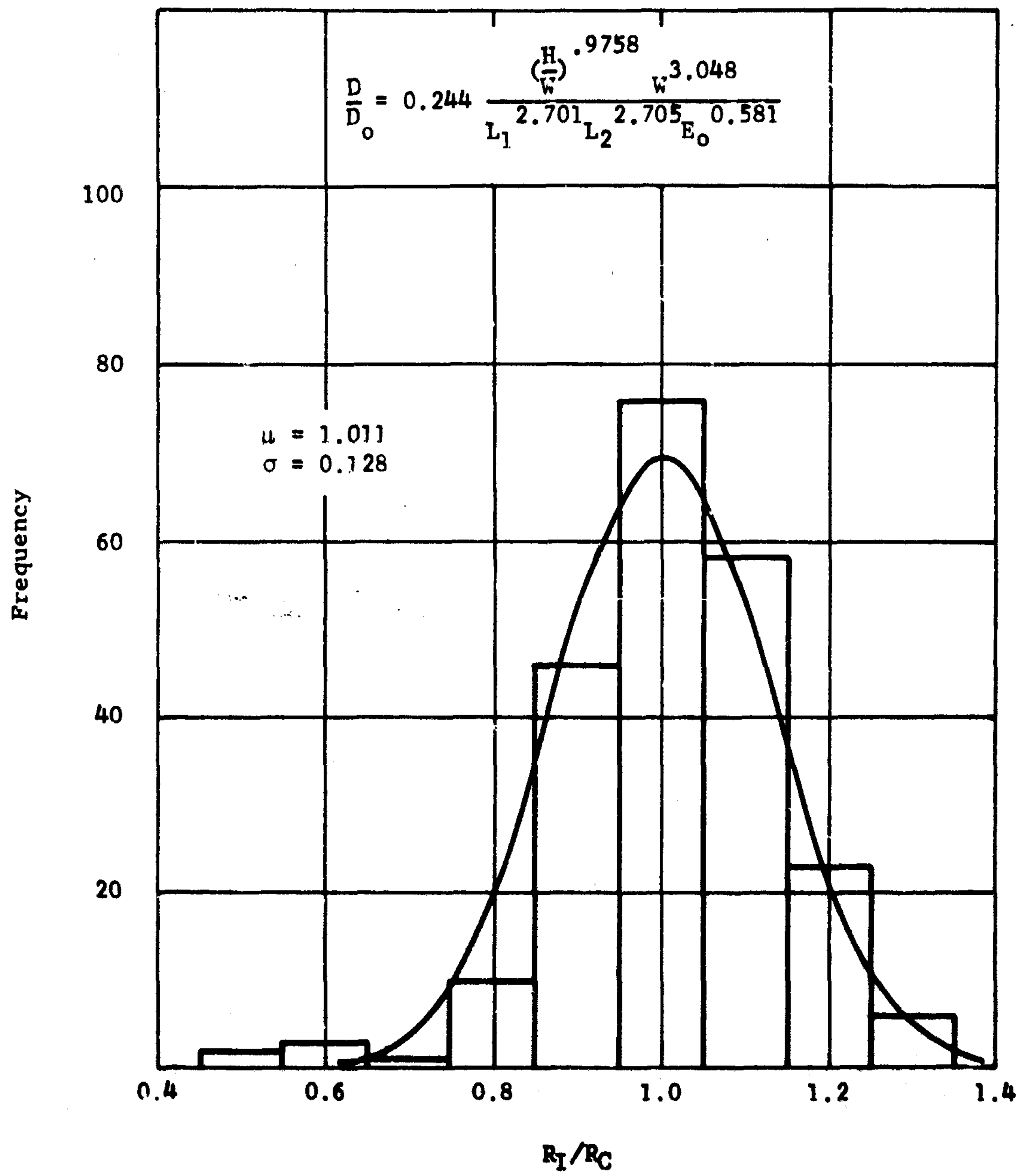

Figure 2. Histogram of ratios between formula values, R_I, and data points, R_C, for Equation 4.

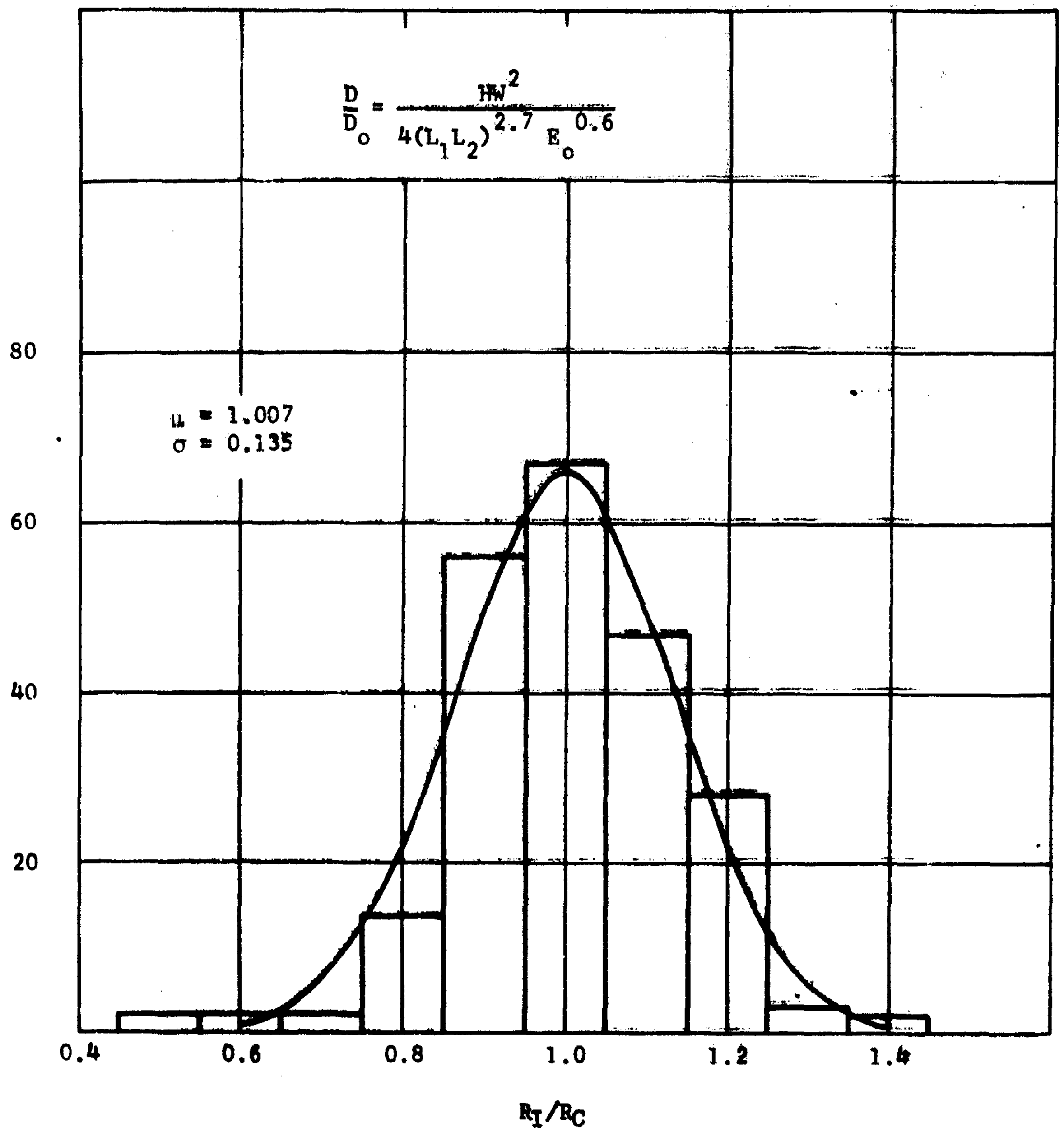

Figure 3. Histogram of ratios between formula values, R_I, and data points, R_C, for Equation 5.

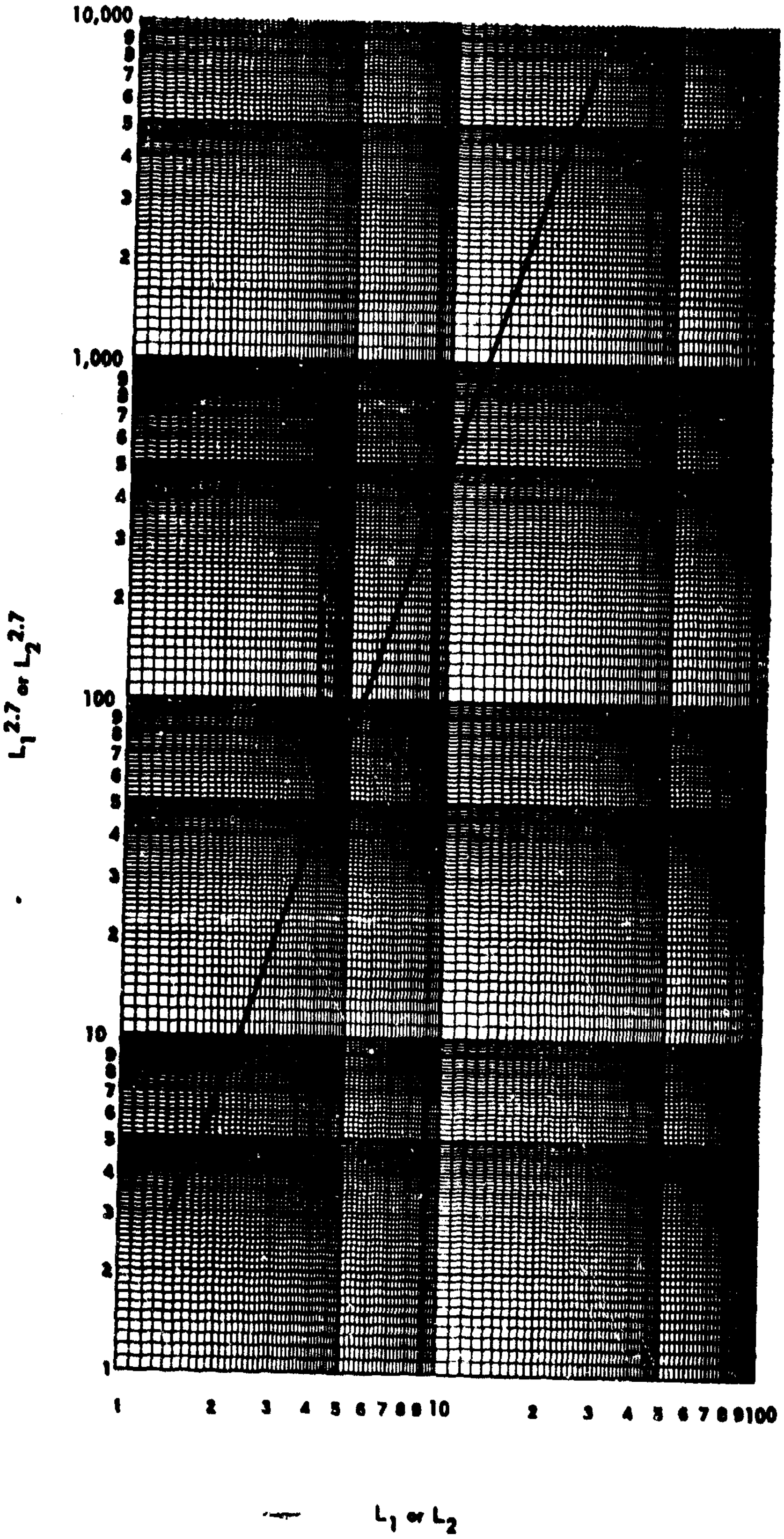

Figure 4. Graph of L vs $L^{2.7}$

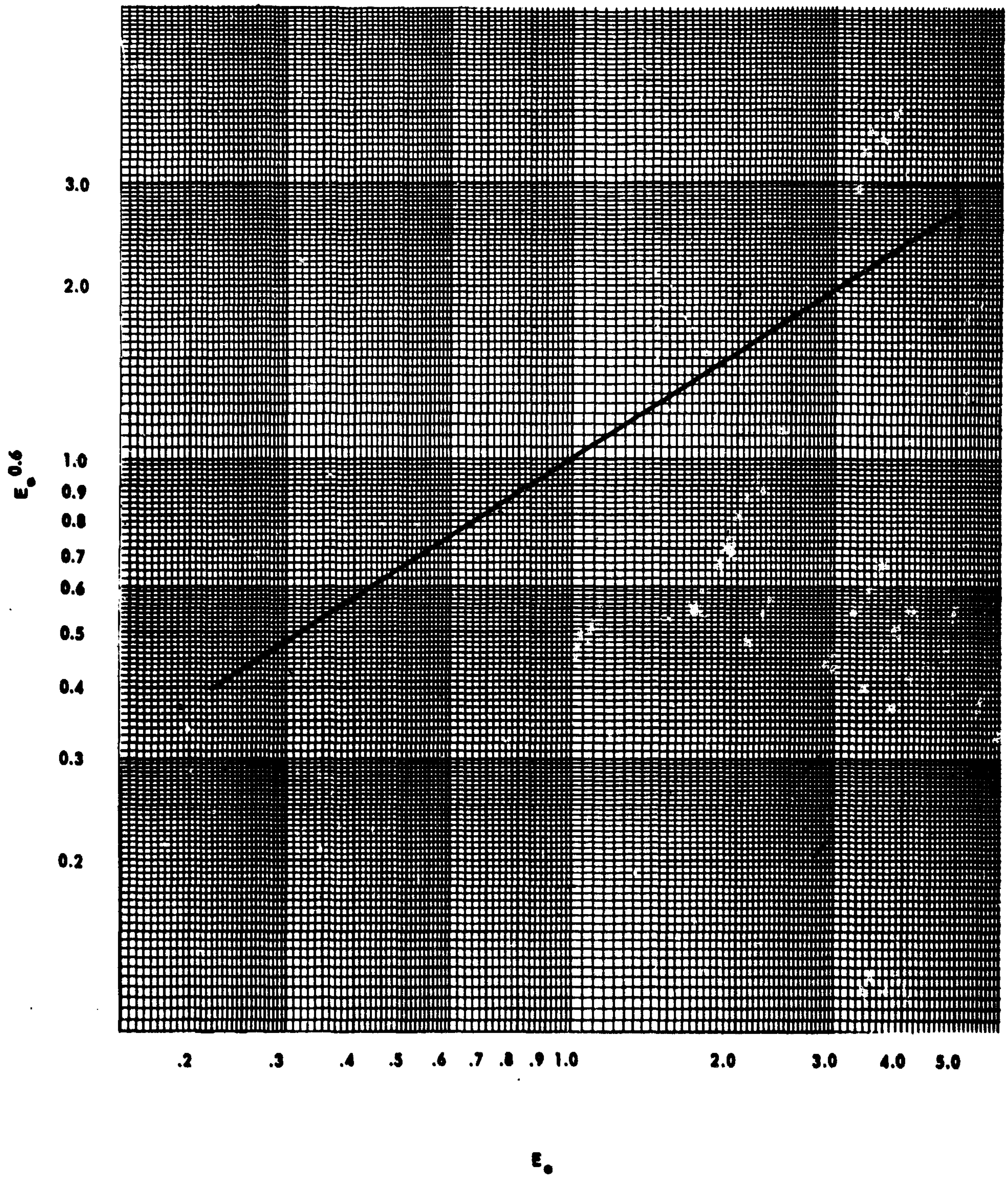

Figure 5. Graph of E_o vs $E_o^{0.6}$.

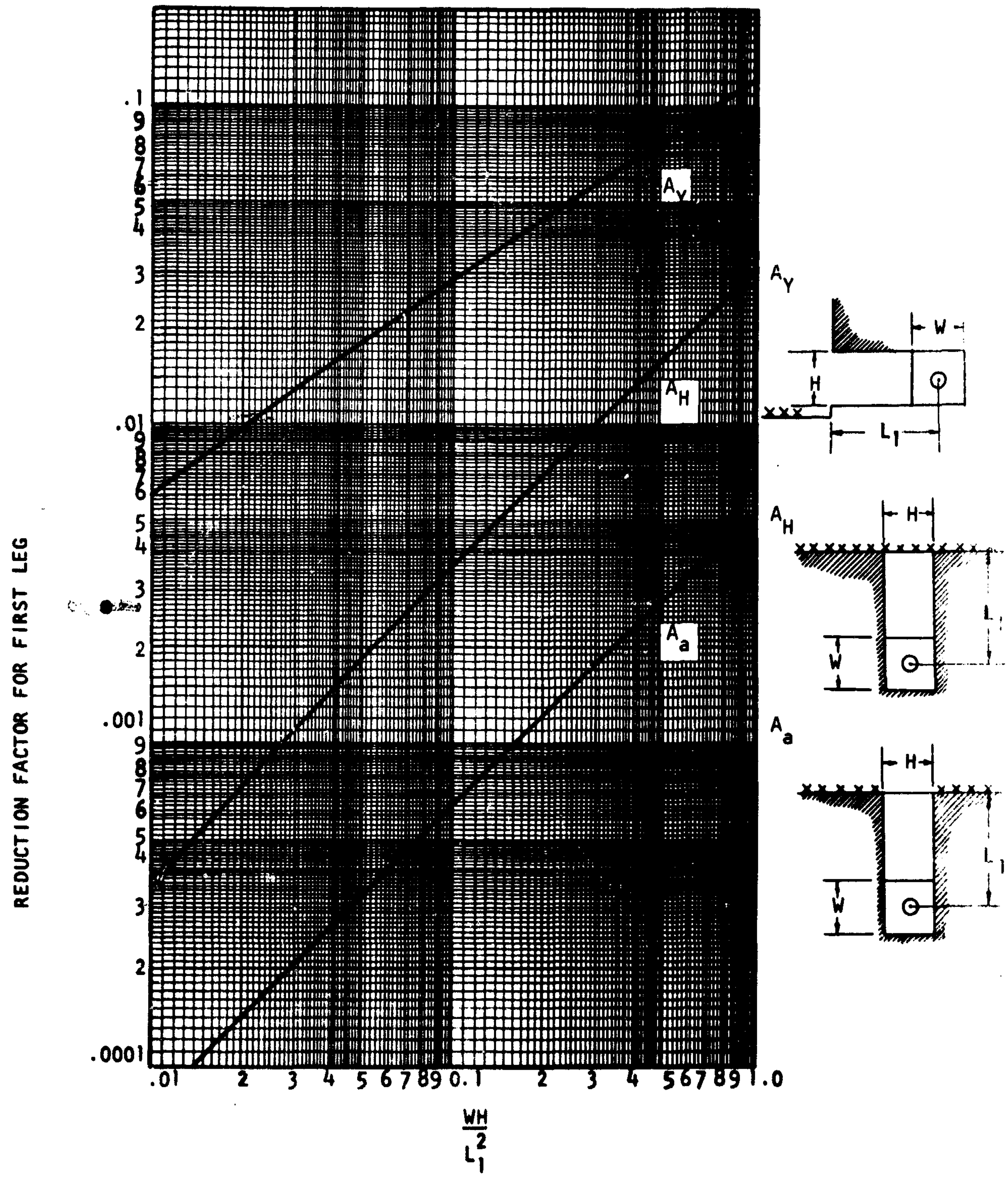

Figure 6. Graph for calculation of source-related attenuation factor